A nearly complete census of intergalactic gas using the kinematic Sunyaev-Zel'dovich effect

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A complete census of baryons in the late universe is a long-standing challenge due to the intermediate temperate and rarefied character of the majority of cosmic gas. To gain insight into this problem, we extract measurements of the kinematic Sunyaev-Zel'dovich (kSZ) effect from the cross-correlation of angular redshift fluctuations maps, which contain precise information about the cosmic density and velocity fields, and CMB maps high-pass filtered using aperture photometry; we refer to this technique as ARF-kSZ tomography. Remarkably, we detect significant cross-correlation for a wide range of redshifts and filter apertures using 6dF galaxies, BOSS galaxies, and SDSS quasars as tracers, yielding a 11 sigma detection of the kSZ effect. We then leverage these measurements to set constraints on the location, density, and abundance of gas inducing the kSZ effect, finding that this gas resides outside dark matter haloes, presents densities ranging from 10 to 250 times the cosmic average, and comprises half of cosmic baryons. Taken together, these findings indicate that ARF-kSZ tomography provides a nearly complete census of intergalactic gas from $z = 0$ to 5. This contribution is a summary of the work already published in Ref. 1.

Keywords: Diffuse radiation; cosmic background radiation; large-scale structure of Universe; cosmology: observations; cosmology: theory

1. Introduction

Over the last decades, precise observations of primordial CMB anisotropies[2] and Big Bang nucleosynthesis studies[3] have set strict constraints on the abundance and distribution of baryons in the early universe. However, a complete census of baryons at late times remains elusive; this is principally due to the intermediate temperature and rarefied character of nearly all cosmic gas, which hinders the detection of baryons outside high-density regions and leaves invisible the majority of cosmological volume. Such is the case that until recently, low redshift studies only detected 70% of the expected amount of baryons.[4–6]

Nonetheless, recent studies have successfully detected baryons outside high-density areas conducting kinematic Sunyaev-Zel'dovich (kSZ) effect observations,[7,8] thermal Sunyaev-Zel'dovich (tSZ) studies,[9,10] low-redshift Lyman-α surveys,[11] and deep X-ray campaigns.[12,13] Despite their success, these works only set constraints on the distribution of baryons at either a few specific redshifts or across a reduced number of line-of-sights, failing to provide a complete picture of cosmic gas in the late universe.

Of the different strategies listed above, throughout this work we set constraints on the properties of intergalactic gas using measurements of the kSZ effect, which refers to the Doppler boosting of CMB photons as these scatter off free electrons moving relative to the CMB rest frame.[14,15] The motivation of using these measurements is that the kSZ effect is sensitive to free electrons independently of the temperature and density of the medium in which these reside, and thus it is uniquely suited to study the large-scale distribution of baryons at low redshift.

Even though the kSZ effect presents significant advantages to observe cosmic gas, it is challenging to extract this signal from observations because the amplitude of kSZ fluctuations is approximately two orders of magnitude smaller than that of primordial CMB fluctuations and the spectral shape of both signals is practically the same. Furthermore, most extraction methods require estimating the peculiar velocity field of intervening matter,[16,17] which is also challenging and adds notable uncertainties. Other approaches circumvent such estimation but require either using cosmological simulations for calibration or modelling and subtracting other effects,[8,18–20] which also introduces substantial uncertainties.

In this scenario, the cross-correlation of angular redshift fluctuations (ARF),[21] which encode precise information about the cosmic density and velocity fields, and CMB observations provides a clean window towards a tomographic detection of the kSZ effect given that systematic uncertainties affecting either of these observables do not present significant correlation. This approach, which we refer to as ARF-kSZ tomography, requires redshift information from either spectroscopic or spectro-photometric surveys as well as theoretical predictions for the large-scale cross-correlation between ARF and the kSZ effect.

2. Results

To extract measurements of the kSZ effect, we start by generating ARF using galaxies from the 6dF Galaxy Survey (6dF),[22] galaxies from the Baryon Oscillation Spectroscopic Survey (BOSS),[23,24] and quasars from the extended Baryon Oscillation Spectroscopic survey (eBOSS)[25] selected at 16 different redshift shells between $z = 0$ and 5. Then, we high-pass filter foreground-reduced *Planck* maps by applying aperture photometry filters of different sizes on the positions given by the aforementioned galaxies and quasars, thereby extracting kSZ signal induced by gas surrounding these sources. This technique also reduces contamination from primordial CMB anisotropies as aperture photometry removes signals that are constant over the size of the aperture. Then, we cross-correlate these maps, finding significant correlation for a wide range of redshifts and filter apertures. After accounting for

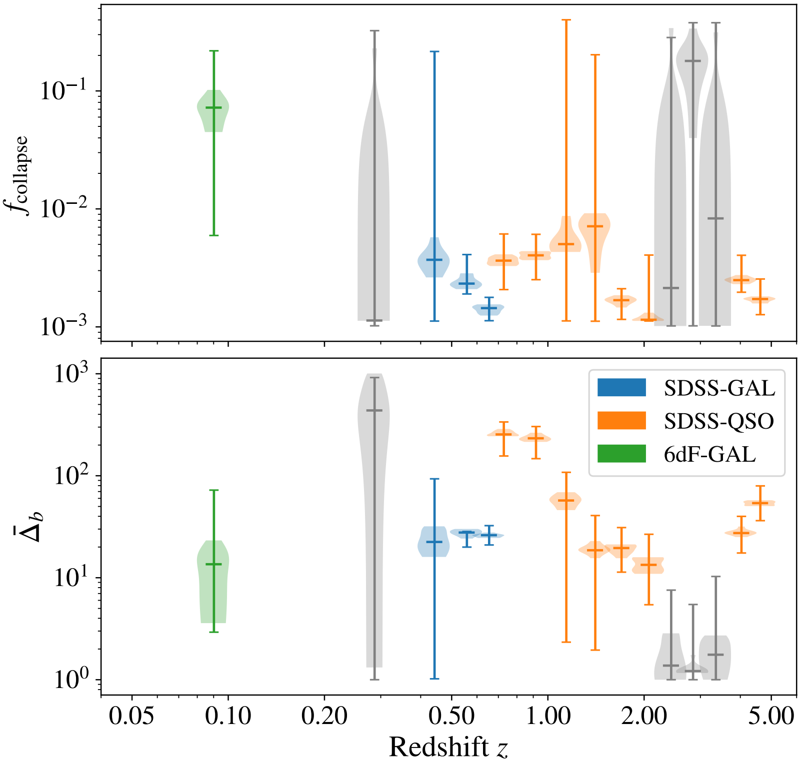

Fig. 1. Fraction of kSZ gas to within dark matter haloes (top panel) and average density of kSZ gas outside these structures (bottom panel). The horizontal bar and size of the shaded regions indicate the average and scatter of results computed using different *Planck* foreground-reduced maps, respectively; green, blue, and orange colours indicate the results for shells containing 6dF galaxies, BOSS galaxies, and SDSS quasars; grey colours denote shells with no significant detection of the kSZ effect; and error bars show 1σ uncertainties for *Planck* COMMANDER map. We find that more than 99% of kSZ gas resides outside haloes and that the density of this gas ranges from 10 to 250 times the cosmic baryon density, which is in agreement with the density of the intergalactic medium according to hydrodynamical simulations.

correlations between different measurements, we find that our measurements yield an 11σ detection of the kSZ effect, which is the highest significance detection of the kSZ effect up to date.

We leverage these measurements to set constraints on the location, density, and abundance of kSZ gas from redshift $z = 0$ to 5. In Fig. 1, we show that more than 99% of kSZ gas resides outside haloes and that the density of this gas ranges from 10 to 250 times the cosmic average, which is in agreement with the density of the gas in filaments and sheets according to hydrodynamical simulations. Then, in Fig. 2 we show that our kSZ measurements are compatible with detecting 50% of

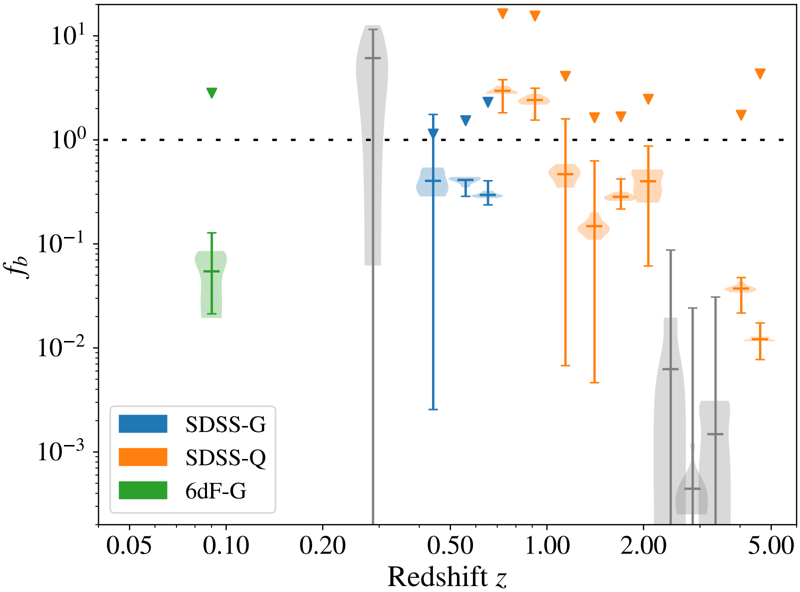

Fig. 2. Fraction of the total abundance of cosmic baryons detected at different redshifts. We use the same coding as Fig. 1. Remarkably, ARF-kSZ tomography is sensitive to approximately 50% of cosmic baryons, which highlights the efficiency of this technique detecting intergalactic gas. The results are well below 50% for the first and last two shells because the number density of sources at these redshifts is very low; in fact, forecasts for f_b when considering an infinite number density of sources (triangles) are compatible among all shells.

cosmic baryons. Taken together, these findings indicate that ARF-kSZ tomography provides a nearly complete census of intergalactic gas from $z = 0$ to 5.

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